Light diffraction in three-dimensional structures fabricated with two-photon 3D photolitography

Abstract

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Polymer structures of microscopic size can interact with visible light in an interesting way. Is it possible to create a filter that transmits only a certain range of wavelengths (colours) or a coating exhibiting different light transmission coefficients when illuminated from two opposite sides? Demonstration, description and explanation of these effects are the basis of the present dissertation.

The described results are the product of over four years of research on diffraction microstructures conducted by the author at the Photonic Nanostructure Facility of the Faculty of Physics, University of Warsaw. This doctoral thesis is divided into three parts, which include the presentation of 3D photolithography technology used to produce microobjects, followed by the description and extensive characterization of two classes of photonic structures, which operation principle is based on the phenomenon of light diffraction. The dissertation shows how the photolithography technique allows for quick design, optimization and accurate production of diffractive elements with given optical properties.

The first part presents a system for two-photon 3D photolithography, which was used to create diffraction gratings. The basic application of this technology is fast prototyping of photonic structures, micro-optical and mechanical components. Photolithography makes it possible to print fully three-dimensional objects made of polymeric resin with a resolution better than one micrometer, i.e. almost a hundred times less than the thickness of human hair. Such dimensions of structures are comparable to the wavelength of visible light, and thanks to that their precise geometry will be of key importance in defining the way these objects interact with electromagnetic waves. As part of this doctoral thesis, the author not only mastered the principles of system operation, but above all had he researched and developed non-standard, repeatable methods of 3D printing - for example, on the surface of a dielectric layered mirror. In addition, another significant achievement was the development of printing method without the use of a mechanical shutter blocking the laser beam, which significantly sped up the whole process.

The second part shows diffraction structures in the form of a regular network of lines or columns of micrometer size, in which the efficiency of light deflection into higher orders depends very strongly on the wavelength and geometry of these structures. They were created by means of the presented two-photon 3D photolithography, which allowed for precise control of their optical properties. When illuminated by white light, as a result of selective diffraction, some wavelengths are deflected by the filters in such a way that the light passing straight ahead contains a narrower colour range, smoothly passing from violet and blue, through green, yellow to orange and red, based on structures geometry. For demonstration purposes, a whole set of filters covering a significant part of the colour palette was created, as well as model grids: red, green and blue, which stand as analogue of the RGB colour pixels known from modern displays. The light transmission in the filters exceeds 80% at the maximum and drops down to less than 5-10% for deflected waves region. The measured

transmission spectra were compared with the results of numerical simulations and analytical calculations, and a very good qualitative and quantitative agreement was achieved. Additionally, it was shown that the transmission characteristics of square symmetry filters do not depend on the polarization of incident light, and that it is possible to produce flat filters (with fixed line height) covering the entire visible range. The materials used (polymers) make the filters biocompatible, and the technology allows them to be produced on various surfaces. Simple geometry of filter structures opens a way to scale their production to industrial processes.

The third part describes the phenomenon of asymmetrical light transmission obtained by combining diffraction elements (presented in the second part) with dielectric mirrors. Since the transmission of such mirrors depends on the light incidence angle, they can be designed to block wavelengths deflected by the diffraction grating and to transmit the undeflected part. The illumination of the structure from the two opposite sides corresponds to the passage of light first through the mirror and then through the grating or in reverse order. In the latter situation, a major part of the diffracted wave can be reflected, making the total transmission significantly lower. This chapter describes the complete process of designing, optimization, manufacturing and measurement of optical properties of such structures. The measured difference in transmission coefficients exceeds 0.7 for light at 780 nm and is higher than 0.2 in the range of 700-850 nm for linearly polarized light. The use of square diffraction gratings makes the asymmetric transmission property independent of polarization, and in that case the measured asymmetry value is greater than 0.55 at 780 nm and 0.2 in the range of 750-820 nm. The results of measurements are supplemented with consistent outcome of numerical simulations.

The research described in this PhD thesis is an important contribution to the development of three-dimensional photolithography of diffractive optical structures. The results have been collected and described in several peer-reviewed scientific articles published in prestigious optical journals. Planed directions of research include the development of filters with tunable spectral characteristics, the design of optical structures for spatial beam shaping and control, as well as their combination with mechanical structures, for example, allowing for the fixing of the optical fibre in the designed place. It will also be important to continuously develop new 3D printing methods, including a wide range of substrates and materials with interesting physio-chemical properties and new functionalities. It can be predicted that the issues of miniaturization of optical systems, their integration with electronic components, as well as light-matter interactions in a micro-scale will be a significant research topic for long, resulting in a plenty of interesting, unexpected results.